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Volume I

ADVANCED STRUCTURAL INSTRUMENTATION

Volume I

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This report presents the results of the development and test of a variety of steady-state strain and temperature sensors specifically aimed at application in hot sections of advanced gas turbines. In each case, the sensors have shown success in the laboratory, and tests and results described herein were designed to simulate the actual turbine environment. Most of the testing was carried out in the UTRC vacuum spin rig which was able to achieve speeds and temperatures characteristic of advanced gas turbines. Volume I is an overview of the sensors, physical description, summary comparison of results and conclusions and recommendations. Volume II gives the details of the sensor fabrication and installation as well as evaluation of the data acquired. The report is divided into the sections each of which gives the details of a specific sensor tested in this program.

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Advanced strain gages were also tested. Two types of wire strain gages were bonded to the turbine disk, the first a conventional commercially available Nickel–Chrome alloy type, and the other, a modified FeCrAl alloy developed by the Chinese. Strain was also measured with several types of sputtered thin film sensors as well as the twin core optical fiber sensor. Speckle photogrammetry was used for noncontacting strain measurement throughout the spin rig testing.

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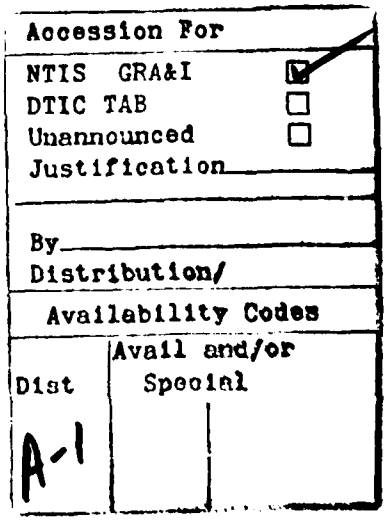
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CONTENTS

Section			Page
I.	EXECUTIVE SUMMARY		1
	1.	INTRODUCTION	1
	2.	OVERALL PROGRAM DESCRIPTION	2
	3.	DESCRIPTION OF SENSORS TESTED	2
	4.	TEST PROGRAM	9
	5.	DISCUSSION OF RESULTS	11
	6.	CONCLUSIONS	15





I. EXECUTIVE SUMMARY

1. INTRODUCTION

The new generation of gas turbines being introduced into service are operating at unprecedented levels of temperature and speed, levels which are dictated by the demand for improved performance, improved durability, and reduced fuel consumption. The materials used in the hot section environment of these engines are working in a regime where small changes in temperature or stress have large effects on component life. It is imperative, therefore, that instrumentation technology be developed to accurately and reliably measure steady strain and temperature in the hostile turbine environment, up to temperatures of 950 K.

This report presents the results of the Advanced Structural Instrumentation (ASI) program, the purpose of which was to demonstrate and test a variety of sensors specifically aimed at application in the hot sections of advanced gas turbines. In each case, the sensors have shown success in the laboratory, and the tests described herein were designed to simulate the actual turbine environment. Most of the testing was carried out in the UTRC vacuum spin rig which was able to achieve speeds and temperatures characteristic of advanced gas turbines. Support for the program in supplying advanced sensors was a team effort comprising UTRC, PWA-N, PWA-S, and DOE.

Temperature sensors tested in the present program include conventional wire thermocouples and an advanced type of thin film thermocouple deposited directly on the test piece. The temperature measuring capability of twin core optical fiber sensor technology has also been demonstrated. Remote sensing of temperature was achieved with a thermographic phosphor technique, and optical pyrometry was used as a control throughout the program. Additionally, the feasibility of advanced concept heat flux sensors on a turbine blade was demonstrated.

Advanced strain gages were also tested. Two types of wire strain gages were bonded to the turbine disk: the first, a conventional commercially available Nickel-Chrome alloy type, and the other, a modified FeCrAl alloy developed by the Chinese. Strain was also measured with several types of sputtered thin film sensors as well as the twin core optical fiber sensor. Speckle photogrammetry was used for noncontacting strain measurement throughout the spin rig testing.

Details of the sensors, application procedures, test techniques, and results are given in the second volume of this report. The material presented in this volume (Volume I) is an overview of the sensors, physical description, summary comparison of results, and conclusions.

2. OVERALL PROGRAM DESCRIPTION

Testing was carried out in five phases, four of which were done in the UTRC vacuum spin rig and the other was carried out on a nonrotating Ferris wheel test device at Pratt & Whitney in Florida. Table 1 summarizes the rig builds and the sensors tested on each one. The test piece used throughout is a first stage high pressure turbine disk from an advanced aircraft gas turbine. For all the tests, gage locations on the disk were at 139 mm, 152 mm, and 165 mm from the center of the disk. At each location strain gages were oriented in both the radial and circumferential direction. The ranges of temperature and speed over which the tests were run are 297 K (room temperature) to 950 K, and zero to 13,200 r/min which are typical of a high pressure turbine. The stationary Ferris wheel (described in Volume II) tests provided risk reduction investigations with the twin core fiber optic sensors and one type of deposited thin film strain gage before conducting the more complex installation required in the rotating environment.

The sections below describe the salient features of each of the sensors evaluated and briefly discuss important fabrication and installation considerations. A descriptive assessment of the performance of each sensor is presented, as well as recommendations for further development or application to current and future instrumentation requirements.

3. DESCRIPTION OF SENSORS TESTED

a. Strain measuring sensors—(1) Commercially available Micro-Measurements type WK-06-062 AP-350 strain gages were used for strain measurement in build 1. These are 1.6-mm gage length modified Karma (nickel-chromium) alloy gages which are fully encapsulated in glass fiber reinforced epoxy phenolic resin. The alloy has a wide range of available self-temperature compensation values. These gages have a maximum normal use temperature of 600 K and were used during build 1, a build to evaluate the operating and thermal characteristics of the spin rig. Thus, they were not expected to

survive when the temperature went over 600 K. The gages were bonded to the grit blasted disk with M-Bond 610 which is an epoxy phenolic adhesive, useful to 644 K for short times.

Data were obtained from the sensors during build 1 at the conditions tabulated below.

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)	X	X	X	X	X
422 K	X	X	X	X	X
589 K	X			X	X
755 K					
950 K					

(2) An advanced wire wound strain gage constructed from the Chinese alloy BHP-700C was tested in the spin rig in build 2. This is a member of the FeCrAl alloy family modified for improved high temperature strain performance at Beijing University in China. This alloy has been laboratory tested up to 950 K and had improved stability over the 644 K to 811 K region. These gages were bonded to the disk with Chinese P12-2 ceramic cement.

Data were obtained from the sensors during build 1 at the conditions tabulated below. Data were not obtained at the highest temperature (950 K) due to leadwire damage.

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)	X	X	X	X	X
422 K	X	X	X	X	X
589 K	X	X	X	X	X
755 K	X	X	X	X	X
950 K					

(3) A significant effort was devoted to sputtering thin film strain sensors directly on the test disk. This is a multi-step process wherein an insulating layer is deposited first, followed by deposition of FeCrAl or PdCr alloy in the sensor grid shape. Cleanliness of the substrate at the molecular level is required to achieve satisfactory performance of the sensor considering both electrical isolation of the grid from ground and accuracy of the grid response to disk strain.

Additionally the deposition process results in complex residual stress fields in the individual layers which may induce separation during sputtering. As described in Volume II, a wide variety of parameters and cleaning methods were investigated, but serviceable strain sensors deposited directly on the disk were not realized for these tests. Early risk reduction experiments were conducted as part of the Ferris wheel testing.

(4) Greater success was achieved with thin film strain sensors sputtered on a thin metallic foil, which was then spot welded to the test piece. In this configuration, the insulating layer is deposited on 0.127-mm-thick Hastelloy-X foil followed by deposition of the sensor grid. The required surface cleanliness was maintained throughout the thin-film fabrication process on the foil resulting in excellent adherence and good initial electrical insulation. The section of Hastelloy-X foil with the array of strain sensors is then stitch welded to the gage section of the disk. It has been demonstrated that the foil is thin enough that it will follow the disk closely in both strain and temperature excursions. Two types of thin film sensors on foil were tested in the present program. The first configuration, an exposed foil, was tested during build 2. The second configuration with an additional layer of insulation sputtered over the metallic sensor was tested during build 3. The conditions over which data were acquired on thin film strain sensors is summarized in the table below. Some sensors survived all testing, but at elevated temperatures, the severe effects of oxidation and insulation leakage biased the strain measurements. These problems are being addressed in other continuing programs.

Build	2	3	2	3	2	3	2	3	2	3
Temp (K)	1200 r/min		6600 r/min		9300 r/min		11,400 r/min		13,200 r/min	
297 K (R/T)	X	X	X	X	X	X	X	X	X	X
422 K	X	X	X	X	X	X	X	X	X	X
589 K	X	X	X	X	X	X	X	X	X	X
755 K	X	X	X	X	X	X	X	X	X	X
950 K		X		X		X		X		

(5) Twin core optical fiber sensors offer several potential advantages for measurement in hostile environments: (a) a single sensor can measure both strain and temperature, (b) since they are optically based, these sensors are not sensitive to electrical interference and are free from constraints of electrically based transducers (isolation from ground, noise, shorting etc.). The sensor is comprised

of a glass fiber with a pair of much smaller waveguides near the center of the fiber. One of these central waveguides (cores) is illuminated with the output from two lasers operating at different wavelengths. At the other end of the sensor, the amount of light at each wavelength appearing in each core is related to both strain and temperature. Straining or heating the fiber changes the coupling between the two cores, resulting in a crosstalk which varies with the wavelength of the incident light.

Testing of these sensors was carried out in two phases. In the first risk reduction phase, the disk with the fiber optic sensors was mounted in a "Ferris wheel" test rig which simulates blade loading on a disk by means of hydraulic rams pulling on each blade slot. This is a stationary test device, consequently bench scale electro–optic systems could be used to support the sensors. For the second phase, the sensors were mounted on the turbine disk and spun up to 8000 r/min. For this application, the electro–optical system was miniaturized to a 7.62–cm–diameter by 10–cm–long package. Furthermore, these components had to operate satisfactorily in an acceleration field up to 10,000 g's.

During the Ferris wheel test, the optical fiber sensors were attached with ceramic cement. The first spin run also utilized fiber sensors attached with ceramic cement while the second run demonstrated practical implementation of ceramic flame–spray methods for the optical devices.

The conditions at which data were acquired for these sensors is shown in the two tables below:

Ferris Wheel Test Conditions (simulated speeds)

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)	X	X	X	X	X
422 K	X	X	X	X	X
589 K	X	X	X	X	X
755 K	X	X	X	X	X
950 K	X	X	X	X	X

Spin Rig Test Conditions

Temp (K)	1200 r/min	6600 r/min	8000 r/min
297 K (R/T)	X	X	X
422 K	X	X	X
589 K	X	X	X

Data were not obtained at the highest speeds and temperatures because of interboard breaks in fiber leads which developed during an 8000 r/min run at room temperature. At the time of failure in the interconnecting fibers, all critical sensor and optical transmitter/receiver functions were in order. However, instrumentation improvements will be required to realize the full two-function (strain and temperature) operation of the twin core optical fiber sensor on a practical basis.

(6) Speckle Photogrammetry is a noncontacting means to measure the displacements of the speckle pattern generated on an object illuminated with a laser. Accomplishing this measurement on the rotating disk required a very short duration, high-intensity light pulse that effectively stopped the rotation. The image of the speckles was recorded photographically. Comparison of the position of individual speckles at low and then high speeds give the displacement which is then converted into strain.

Speckle data were acquired at the following test points:

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)	X	X	X	X	X
422 K	X	X	X	X	X
589 K	X	X	X	X	X
755 K	X	X	X	X	X
950 K	X	X	X	X	X

The speckle photogrammetry provided the most comprehensive results and should be considered as the reference measurements for these experiments; however, the discrepancy in strain levels in the radial direction between speckle and resistance measurements has yet to be resolved. Although the unattached, remote measurement method may be difficult to implement in a flight environment, this remote, noncontacting method of implementation enables it to function in the most extreme and hostile conditions.

b. Temperature measuring sensors—(1) Platinum-Platinum, 10% Rhodium thin film thermocouples were sputtered directly on the disk for build 1. Application of these sensors required initial deposition of an insulating layer followed by deposition of the elements of the thermocouple junction.

Achieving both durable bonding of the films (to each other and to the disk) and electrical isolation from the disk surface were found to be mutually exclusive requirements. The noble metal films are chemically inactive and, therefore, even less adherent to the insulation layer than the strain gage alloy films described previously. Adherence is, therefore, even more sensitive to any trace of surface contamination on an atomic scale. Due to size considerations, techniques used successfully to install thin-film thermocouples on turbine blades could not be applied on the turbine disk. These techniques involve application of preliminary high-temperature alumina-forming coatings such as NiCoCrAlY alloys at temperatures above 1300 K. The sensors finally installed in build 1 on the turbine disk (after initial trial films delaminated) were characterized by low resistance to ground. Adherence was apparently due to penetration of the platinum and platinum-rhodium films through cracks and pinholes in the insulation layer. The sensors survived the spin testing and provided temperature readings that were reasonable, but the leakage to ground indicated the presence of secondary thermocouple junctions. The film thermocouples, therefore, measured an average temperature over the film length rather than a point temperature at the desired location.

Conditions at which these sensors were evaluated are shown below:

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)	X	X	X	X	X
422 K	X	X	X	X	X
589 K	X	X	X	X	X
755 K	X	X	X	X	X
950 K	X	X	X	X	X

(2) Conventional Chromel-Alumel (Type K) wire thermocouples were used throughout the program to measure local temperature at strain gage locations and to monitor disk temperature distributions. In most applications, the individual wires were tack welded directly to the disk. The thermocouples were located within 1.5 mm of the gages whose temperatures they were to monitor.

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)	X	X	X	X	X
422 K	X	X	X	X	X
589 K	X	X	X	X	X

755 K	X	X	X	X	X
950 K	X	X	X	X	X

(3) An optical pyrometer was used throughout the program as a noncontacting temperature indicator. This was used at temperatures above 589 K to corroborate the average temperature in the disk web where the rotating sensors were located.

Temp (K)	1200 r/min	6600 r/min	9300 r/min	11,400 r/min	13,200 r/min
297 K (R/T)					
422 K					
589 K	X	X	X	X	X
755 K	X	X	X	X	X
950 K	X	X	X	X	X

(4) As noted in Section III A5, the twin core fiber optic sensors have simultaneous strain and temperature sensitivity when excited with illumination at two wavelengths. This feature was exploited to determine temperature at the conditions shown in the table below:

Temp (K)	1200 r/min	6600 r/min	8000 r/min
297 K (R/T)	X	X	X
422 K	X	X	X
589 K	X	X	X

(5) The use of thermographic phosphors for rotating temperature measurement in the turbine environment was demonstrated using the ASI test hardware. This technique measures the temperature dependent rate of decay of certain spectral lines of a phosphor bonded to the disk when the phosphor is excited with an ultraviolet laser. This remote sensing system uses a pulsed UV laser to energize a 10 mm phosphor spot on the disk and then records the phosphor emission during the brief time that the spot is within the field of view of the detector. Data acquisition for these tests was carried out by personnel from Los Alamos National Laboratory and Oak Ridge, and is reported elsewhere, Reference 1.

c. Heat flux sensors—Advanced turbine blade heat flux sensors were evaluated for fabricability and operational durability during the ASI program. (Since the tests were conducted in a vacuum, there was

no air flow around the blade which would enable heat flux to be measured.) Two types of sensors (described in Volume II) were fabricated from fine wire thermocouples. The sensors were installed into two-piece blade halves prior to bonding of halves together and final machining. The instrumented blades were fitted into the ASI disk during build 2 and the sensors monitored for survival and noise level over the full range of test conditions.

4. TEST PROGRAM

a. High speed spin rig—The high speed spin rig at UTRC is built for structural dynamic testing of a wide range of rotating components. Turbomachinery components, propellers, and helicopter blades were given foremost consideration during design but other applications such as labyrinth seal tests were also planned. Since it is not designed for failure testing, it was constructed above ground with the drive system and instrumentation located below the vacuum chamber thus leaving the top surface completely unobstructed and available for various optical measurement techniques. The vacuum chamber is 3 meters diameter by 1 meter high although test piece diameter may be limited by the containment ring diameter or access port size. Test experience to date, includes speeds up to 13,200 r/min, but with appropriate modifications, operation up to 30,000 r/min is possible. The test chamber is maintained at vacuum conditions to minimize drive power requirements, to evaluate structural properties of blades without aerodynamic effects, and to reduce the explosion hazard resulting from entrapped oil vapor or explosive dust generated by accidental rotor failure.

For the Advanced Structural Instrumentation testing, capability was added to the rig to heat the test piece up to 950 K, which necessitated heat shielding and cooling systems to confine the heat to the test chamber itself. A motor assembly consisting of disk, blades, and side plates from an aircraft first stage high pressure turbine was used as the test piece throughout the program.

The number and variety of evaluated sensors required that the tests be carried out in a series of rig builds, a build consisting of a group of sensors mounted on a disk and tested over the complete operating envelope. Table 1 summarizes the builds and the sensors that were tested. As familiarity was gained with the thermal response of the rig, it was feasible to make modifications between builds to correct or modify operating characteristics as required for the specific test.

TABLE 1. ASI BUILD NUMBER & SENSOR LIST

Spin Rig Build No.	Disk Mounted Sensors	Remote Sensors
1	Thin Film T/C Wire T/C Wire Strain Gages	Optical Pyrometer Speckle Photogrammetry
2	Chinese Wire S/G Thin Film S/G on Foil Back-No Overcoat Wire T/C Heat Flux Sensor on Blade	Optical Pyrometer Speckle Photogrammetry
3	Thin Film S/G on Foil Back-Overcoated Thermographic Phosphors Wire T/C	Optical Pyrometer Speckle Photogrammetry
4	Thin Film S/G on Foil-Overcoated Twin Core Fiber Optic Sensors Wire T/C	Optical Pyrometer
Ferris Wheel	Thin Film S/G Direct Deposition Twin Core Fiber Optic Sensors	

b. Description of Ferris wheel—The Ferris wheel is a static test fixture that allows simulation of blade-pull, and heating on a disk without the complexity of engine installation, slip rings, lead routing, etc. The Ferris wheel comprises a massive circular frame fitted with as many hydraulic cylinders as there are slots in the disk to be tested. The inner end of each of the hydraulic cylinder rams is attached to a fir tree block that matches the slots in the disk rim. Provision is made at the bore of the disk for electric heaters to simulate temperature excursions that the disk experiences during engine operation. During a test, hydraulic pressure in the rams is cycled to simulate the centrifugal pull of the blades which load the disk. The complete assembly can be oscillated slowly about its axis to reduce the convection induced thermal gradients. Ferris wheel testing is advantageous because instrumentation leadwork can be connected directly to the data acquisition system with no intervening slip ring, and there is no requirement to make the acquisition system fit into the confined space of the rotor or operate in the hostile rotor environment. Results from the risk reduction tests with this facility are given in Volume II.

5. DISCUSSION OF RESULTS

Figures 1 and 2 compare the output of various strain sensors at a given radius for variations in nominal web temperature. The difference in strain reading between the maximum speed of 13,200 r/min and the reference low speed of 1200 r/min is plotted as a function of temperature. Thus effects of drift and zero shift because of temperature are minimized. In the sensor identification system, the leading numeral indicates the build during which the data was acquired. The last pair of letters identify the type of sensor:

WG = Commercial strain gages

CG = Chinese alloy wire gages

FG = Thin film gages deposited on foil backing

SP = Strain from speckle photogrammetry

FO = Twin Core Optical Fiber Sensor

The difference between acceleration and deceleration is significant for the high temperature runs where there is a radial gradient which changes with time in the disk. Since heat is applied to the relatively thin web, early in the run the gradient may be quite large with the massive bore remaining cool even as the web is hot. This gradient generates stress from the difference in thermal growth bore to rim. As the run progresses in time, the bore heats up and the gradient induced stresses are reduced.

Obviously, several different types of sensors produced useful data over significant portions of the speed and temperature range of the test, but only the speckle obtained data over the entire range of speed and temperature. Additionally, there is no agreement in the general level of strain indicated by most of the sensors particularly at room temperature. Those cases where there is substantial difference between sensors even at low temperature occur after the sensors have been cycled one or more times to high temperature. Notice the shaded region in the background which represents the strain calculated by a finite element analysis. The analysis assumes that there is no in plane bending in the disk (a condition which may not be satisfied in the spin rig configuration), and part of the shaded region represents the bending which may exist in the disk. Additionally, heating the disk in the web region causes a radial thermal gradient, the bore remaining cooler than the web (particularly early in

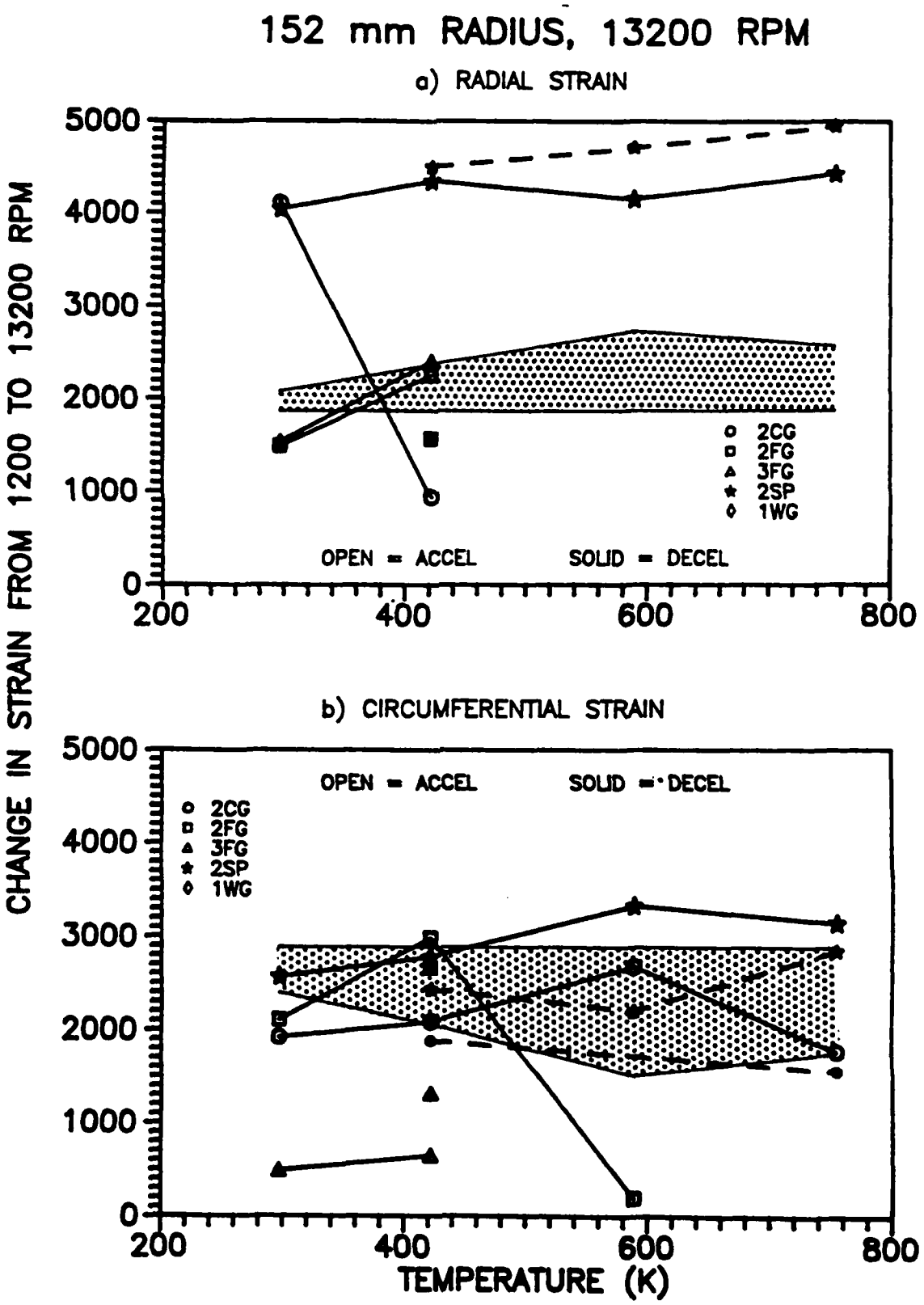


Figure 1. Change and strain vs. temperature

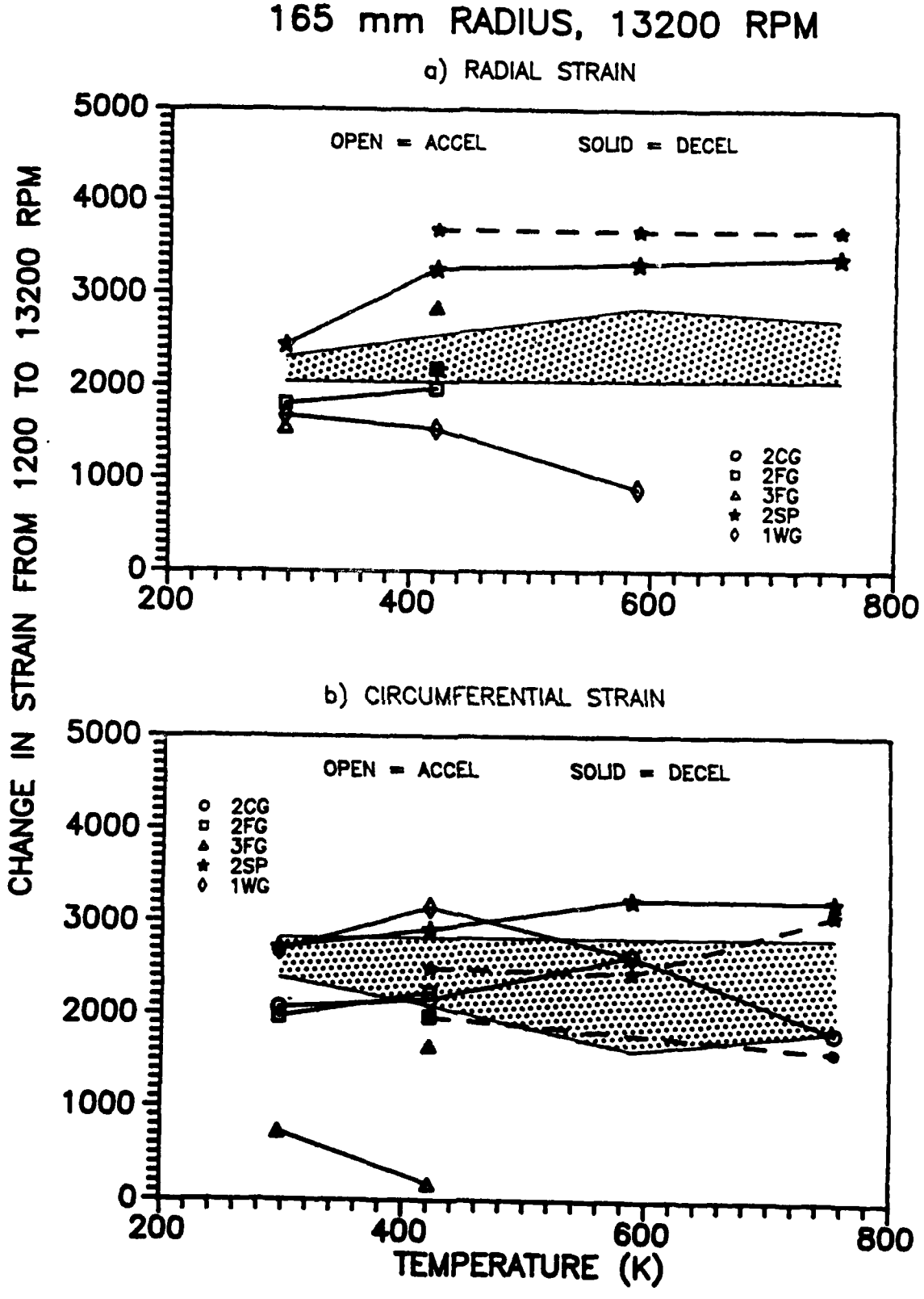


Figure 2. Change and strain vs. temperature

the run). This gradient induces a stress distribution because of the thermal fight between bore and web. Since the actual gradient is not known, the analysis was carried out using several possible temperature distributions each one of which leads to a different strain distribution. Thus a range of strain is shown which includes the level which might be expected from in-plane bending, and for the high temperature runs, the strain arising from the thermal gradients. Although the speckle is the only method that yielded strain results at 950 K, the film gages survived several excursions to 950 K but were precluded from yielding useful data at that temperature by the excessively large swings of apparent strain due to temperature which saturated the data acquisition system.

Figure 1 shows the measured change in strain between 1200 r/min and 13,200 r/min for sensors at 152 mm radius in both the radial (a.) and circumferential (b.) directions for the different temperatures that were run. Notice that the open symbols (solid lines) are data that were recorded during an accel, and the solid symbols (dotted line) are data acquired during decel. As mentioned above, strain due to radial thermal gradients tends to be larger during the accel portion of a run than during the later decel. The speckle results in Figure 1a, show good agreement between accel and decel but at a level which is approximately 2500 microstrain higher than the disk mounted resistance sensors. For reasons which are still unknown, the speckle results in the radial direction were consistently higher than the resistance gages throughout the program. Even though results were not obtained over the entire temperature range, the points shown in Figure 1a for the build 2 and 3 foil backed thin film gages are typical. In the circumferential direction (Fig. 1b), there is much better agreement between speckle and the resistance gages. The erratic build 3 foil gage and the build 2 foil gage results above 400 K are judged to be a result of gage or installation deterioration. The shaded area in the background of each curve is the result of a finite element analysis of the disk.

Figure 2 is a similar comparison to Figure 1 except at a Radius of 165 mm. Again, the speckle results in the radial direction are somewhat higher than the other sensors of the analysis, whereas the circumferential strains agree much more closely (except for the build 3 foil gage which appears to be failing).

The general quantitative agreement between these modified thin film sensors and the others (including the noncontacting) indicate that this is a useful technique for applying thin film sensors to large test pieces.

Figure 3 compares results from several sensors over a more limited range than the previous curves; the strain difference between 6600 r/min and 1000 r/min, and measurements as a function of temperature from room temperature (297 K) up to 590 K. The data, in this case, are results from the twin-core optical fiber sensor. Except for the extreme results from the thin film gages at 420 K, all sensors tend to agree in level. The large discrepancy between the acceleration and deceleration measurements with the twin-core device at room temperature may stem from the fact that this measurement occurred during the first spin to 6600 r/min and may exhibit some attachment induced hysteresis.

6. CONCLUSIONS

1. The sensors indicated similar levels of strain and temperature while operating in the hostile turbine like environment.

2. Most of the experimental difficulties arose from application specific problems rather than the operational physics of the sensor.

3. ASI demonstrated that the physical principles of the sensors are valid, but the sensors are not yet ready for routine test use.

4. Sputtering sensors on foil for subsequent attachment to the test piece is a successful approach to strain measurement and overcomes problems associated with cleaning large test objects.

5. With reduced temperature sensitivity (development currently in progress), the foil backed thin film strain gages are the closest to being ready for routine use.

6. Testing of the heat flux sensors demonstrated that these sensors can be incorporated in turbine airfoils during blade fabrication.

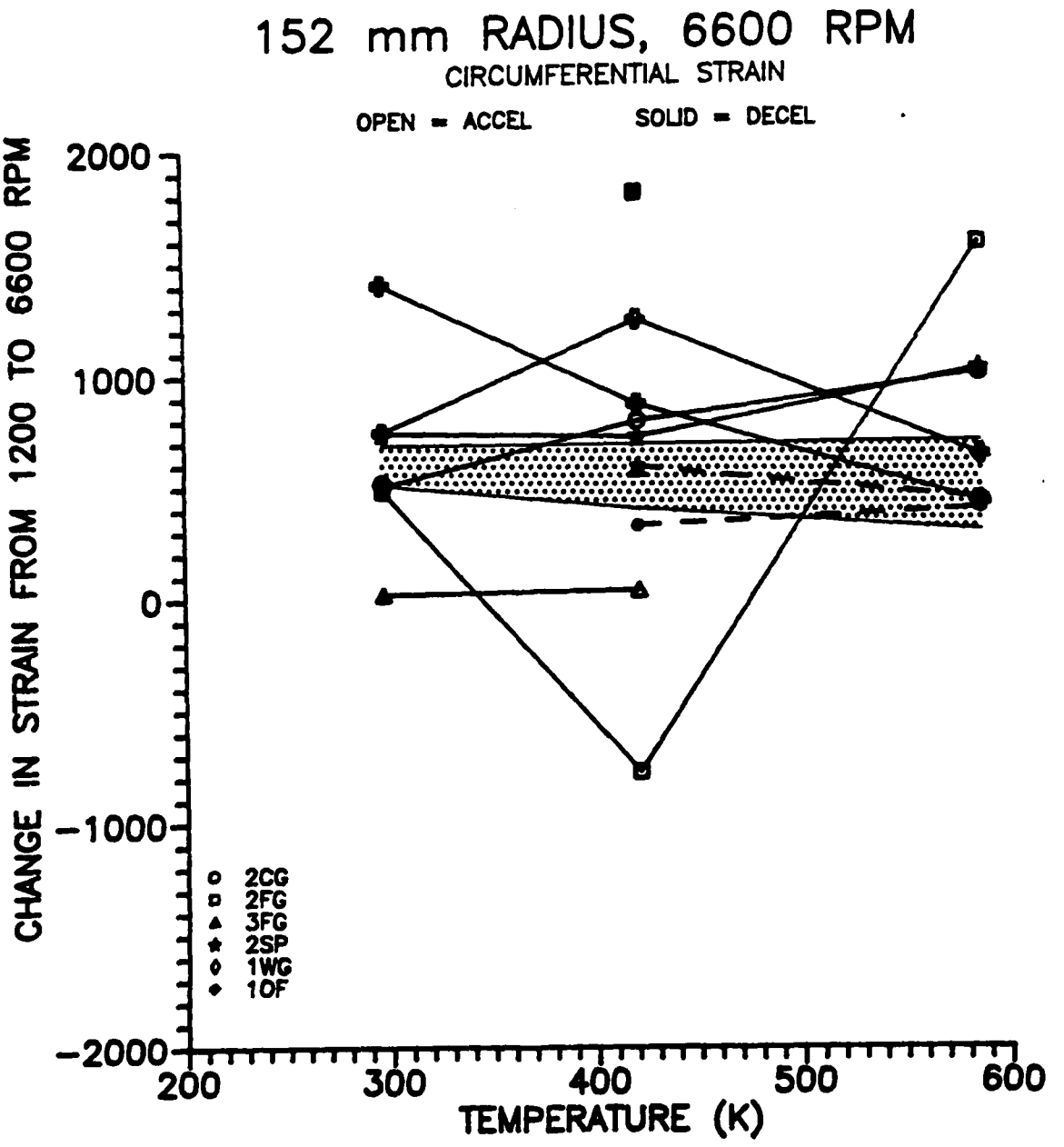


Figure 3. Change and strain vs. temperature

7. Speckle photogrammetry exhibited the most reproducible data over the full range of temperature and speed. The significant difference in measured radial strain between the speckle and resistance strain gages (and analysis) has not been explained.

8. The twin core optical fiber sensor functioned satisfactorily with potential for operation at much higher speeds and temperatures. Further testing was limited by problems with instrumentation and connecting leadwork, not by the sensors.

9. Flame spray attachment methods can be used with optical fiber sensors.

10. Risk reduction tests on the Ferris wheel indicate that the twin core optical fiber sensors may have the potential for use at higher temperature.

11. ASI demonstrated the capability of miniaturizing rugged electro–optics required to energize and detect the fiber optic sensor signals.

12. The ASI rig has proved to be a valuable tool for instrumentation development of many types, e.g. the thermographic phosphor temperature measurement.

REFERENCES

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